ASSESSING CHANGES IN COASTAL ECOSYSTEM SERVICES: A CASE STUDY OF THE IMPACT OF LAND COVER CHANGE IN FANGYUAN WETLAND, CHANGHUA.

Lin, Li-Chung*[1] and Wang, Su-Fen[2]
[1]Master's Student, Department of Geography, National Changhwa University of Education,
Email: ngt10912@gmail.com

[2]Professor, Department of Geography, National Changhwa University of Education,
Email: sfwang@cc.ncue.edu.tw

KEY WORDS: land use and cover change, ecosystem service, Coastal Blue Carbon, Habitat Quality, scenario analysis

ABSTRACT: Coastal wetlands play a pivotal role in providing numerous ecosystem services, particularly with mangrove forests acting as substantial blue carbon sinks in response to greenhouse gas emissions. However, they are not immune to severe impacts arising from human development, leading to disruptions in their natural environment. Within Changhua County's Fangyuan Wetlands, the intrusion of non-native mangrove species has contributed to siltation and landward encroachment, resulting in reduced habitat for species in the tidal flat area and the emergence of ecological conflicts.The primary objective of this study is to examine a span of 27 years' worth of land use and land cover (LULC) changes in the Fangyuan Wetlands attributable to the proliferation of mangroves and assess their repercussions on coastal ecosystem services. This research entails the generation of LULC maps spanning from 1996 to 2023, accomplished through satellite imagery analysis. Furthermore, it involves the estimation of ecosystem services for each year, employing two sub-models of InVEST: "Habitat Quality" and "Coastal Blue Carbon." Finally, the study conducts an in-depth analysis of the spatial distribution and quantitative alterations in ecosystem services under various thinning scenarios.The outcomes of this investigation reveal that habitat quality values for the years 1996, 2006, 2017, and 2023 stand at 0.9039, 0.3723, 0.2296, and 0.2636, respectively. Concurrently, carbon stock values for these same years are documented as 1118.96, 2065.58, 6833.95, and 10806.87 Mg C. Impressively, the cumulative net carbon sequestration between 1996 and 2023 tallies to 9687.90 Mg C. Scenario analysis underscores a positive correlation between habitat quality and the thinning ratio of the red mangrove area. Conversely, carbon stock demonstrates a negative correlation with the thinning ratio of the mangrove area. Notably, among these factors, thinning of the mangrove area exerts a more pronounced influence on ecosystem services compared to the position factor. This study offers valuable insights into the historical shifts in habitat quality and the contribution of mangroves in the Fangyuan Wetlands to coastal blue carbon, accentuating the inherent trade-off relationship. Furthermore, it underscores the imperative need for prudent thinning practices and future-oriented planning in ecological management to effectively address evolving ecological dynamics.

1. INTRODUCTION

1.1 Motivation

In the realm of international mangrove research, the spotlight has often been on their degradation due to changes in land use, while studies addressing the decline in habitat quality have been rather scarce. Although there is some literature on mangrove ecosystem services at the domestic level, these studies tend to primarily center around carbon balance and sequestration (Lin, 2019; Lin, 2018; Huang, 2016; Lee, 2015). There has been relatively less exploration into the complex interplay between coastal blue carbon and the quality of tidal flat habitats provided by mangrove ecosystems. The invasion of mangrove forests into the Fangyuan Wetland in Changhua has presented a formidable ecological challenge, directly impacting the overall ecosystem services of the region. It is imperative to comprehend how the changes in land cover brought about by mangrove plantation influence habitat quality and the ensuing benefits and variations in blue carbon ecosystem services within Fangyuan Wetland. Furthermore, it is crucial to contemplate and devise appropriate planning strategies aimed at optimizing the ecological services that wetlands have to offer.

1.2 Aims

Given the research motivation mentioned earlier, this study aims to:

1. **Understand LULC Changes:** Analyze satellite images from different time periods to comprehend how mangrove growth relates to land use and cover (LULC) changes and their impact, creating a mangrove distribution map.
2. **Evaluate Ecosystem Services:** Utilize the InVEST ecosystem services model to assess habitat quality and coastal blue carbon benefits under various land use scenarios in Fangyuan Wetland over different time periods.
3. **Simulate Ecosystem Service Provision:** Simulate and assess the overall and spatial distribution of ecosystem services under different mangrove thinning scenarios through scenario analysis.

These objectives form the core of our research, providing insights into the dynamic relationship between mangrove growth, land use changes, and their effects on ecosystem services in Fangyuan Wetland.

1.3 References to Related Work

In recent years, the escalating impact of climate change has become a global concern. The UNFCCC's Paris Agreement, adopted during COP21 in 2015 and effective since 2020, commits 77 nations to achieve net-zero greenhouse gas emissions by 2050. Efforts to mitigate emissions and employ carbon-neutral techniques, including carbon sequestration in coastal ecosystems known as blue carbon sinks, are gaining importance.Blue carbon encompasses carbon stored in coastal ecosystems like tidal marshes, mangrove forests, and seagrass beds, which sequester more carbon than land-based ecosystems (McLeod et al., 2011). Among these, mangrove wetlands are vital, supporting diverse ecosystems and serving as significant carbon sinks (Twilley et al., 1992). Despite their ecological importance, mangroves have been excluded in landscape-level carbon assessments due to limited data and coverage (Barbier et al., 2011). Over time, they have faced degradation from human-induced environmental damage and climate change, endangering their existence. Nonetheless, mangroves are highly adaptable to saline water and low-oxygen sediments, making them resilient colonizers (Tomlinson, 1986). Many mangrove forests along Taiwan's west coast, including those in Changhua County, were intentionally planted in 1983 by the Water Resources Agency of the Ministry of Economic Affairs for flood protection. They primarily span the coastal areas of Fobao and Fangyuan. Over time, sedimentation and land conversion have led to habitat loss and ecological conflicts (Changhua County Government, 2014).

This study aims to track changes in land cover within Changhua County's Fangyuan wetlands, Taiwan. Using the InVEST model, which includes sub-models for "habitat quality" and "coastal blue carbon," we assess and evaluate ecosystem service provision in the Fangyuan wetlands over different time periods. Our research seeks to understand the connection between land use changes and ecosystem services, with a focus on exploring trade-offs among various ecosystem services.

The InVEST model (Integrated Valuation of Ecosystem Services and Tradeoffs) has been widely employed in global ecosystem service assessments. For example, Hoyer and Chang (2014) used it to project freshwater ecosystem services in Oregon's Tualatin and Yamhill watersheds, considering urbanization and climate change up to 2050. Rimal et al. (2019) analysed land use changes in Nepal's Koshi River basin from 1996 to 2016, utilizing Landsat imagery and the InVEST model to quantify shifts in food production, carbon storage, and habitat quality-related ecosystem services. In another study, Bera et al. (2022) investigated ecosystem service values and carbon sequestration dynamics in India's Sundarbans mangrove ecosystem using time-series satellite data and the InVEST Carbon Storage model. Domestically, Chan et al. (2020) applied the InVEST model to assess carbon sequestration, water production, and soil retention in Taiwan's Lianhua Lake area between 1995 and 2015. Similarly, Chen et al. (2021) evaluated the impact of land use changes in Taiwan's Pizhen area from 1999 to 2018 on ecosystem services using Landsat 7 satellite imagery and the InVEST model.

2. MATERIALS AND METHODS

2.1 Study area

The Fanyuan Wetland Mangrove Forest is located on Taiwan's western coast in Changhua, near the Erlin Stream estuary (coordinates: 23°937’N~23°927’N, 120°307E~120°314E). It falls under the category of coastal wetlands, including estuaries, tidal flats, and non-native mangrove swamps, as per the Ramsar Convention (Changhua County Government, 2020). Initially planted in 1983 by the Ministry of Economic Affairs' Water Resources Agency, this mangrove forest now covers more than 45 hectares with trees over 3 meters tall. However, the spread of seedlings into drainage channels and their expansion has led to silt buildup on the tidal flats and land encroachment. This has reduced wetland area and functionality, impacting species habitats on the tidal flats (Changhua County Government, 2014).

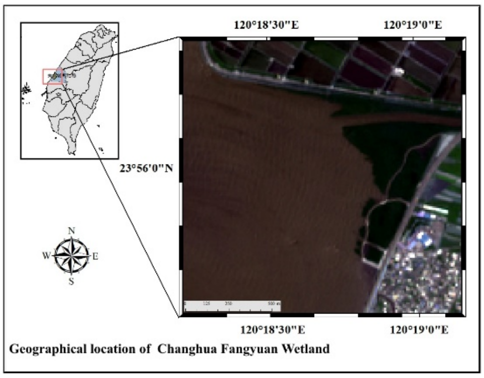

Figure 1. Study area.

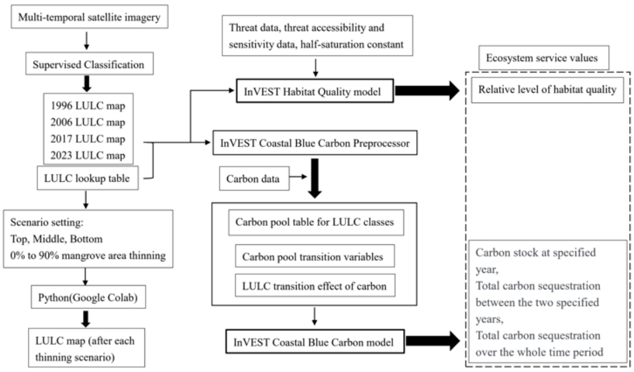

Figure 2. Research workflow diagram.

2.2 Methodology

In this study, we focused on two crucial ecosystem services: carbon sequestration from mangrove blue carbon and habitat quality in tidal flats, both essential for the research area's sustainability. Our research began by analysing land use changes in Changhua Fangyuan Wetland's coastal area. We utilized supervised classification on using satellite images from 1996, 2006, 2017, and 2023, creating land use maps to understand spatial patterns. We used the InVEST model's "Habitat Quality" and "Coastal Blue Carbon" sub-models to estimate ecosystem services for each year, analysing the results in ArcGIS 10.2. We also simulated different mangrove thinning scenarios within the study area, observing changes in the spatial distribution and overall quantity of ecosystem services under various scenarios, as shown in Figure 2 of our research workflow.

2.3 Fangyuan Wetland land use map

To create the necessary land use maps for the InVEST model, we used Landsat 5 (Thematic Mapper, TM) and Sentinel-2 satellite images covering our study area. Landsat provided a 30-meter resolution, while Sentinel-2 had a finer 10-meter resolution. Landsat 5 imagery from 1996 and 2006 was obtained from the United States Geological Survey (USGS) website, and for 2017 and 2023, we used Sentinel-2 images (S2A_OPER_MSI_L1C) from the European Space Agency (ESA). To ensure consistency, all images were resampled to 10 meters. We then applied supervised classification with the Maximum Likelihood Method to each image, resulting in land cover maps for the Fangyuan Wetland. These maps categorized land cover into two types: Mangrove and Tidal Flat.

2.4 InVEST model and input

To model coastal blue carbon ecosystem services, this study utilized InVEST-v3.13.0 to evaluate the quality of tidal flat biological habitat and coastal blue carbon services within Fangyuan Wetland. Below, we provide an outline of the parameters and data required for the two sub-models, with the content primarily referenced from the InVEST 3.13.0 User Manual (Natural Capital Project, 2023).

2.4.1 Habitat Quality model: InVEST models habitat quality and rarity as surrogate indicators of biodiversity, ultimately estimating the extent of habitats and vegetation types across the entire landscape, along with their degradation status. The main equation used for calculating habitat quality is as follows:

$$D_{XJ} = \sum_{r=1}^{R} \sum_{y=1}^{Y_r} \left(\frac{w_r}{\sum_{r=1}^{R} w_r} \right) r_y i_{rxy} B_x S_{jr} \tag{1}$$

$$Q_{xj} = H_j \left(1 - \left(\frac{D_{xj}^z}{D_{xj}^z + k^z} \right) \right) \tag{2}$$

where D_{XJ} = habitat degradation index
Q_{xj}= habitat quality
H_j = habitat suitability
k = scaling parameters
z= scaling parameters

The required input data in habitat quality model including: LULC map, threat data (threat factors, maximum threat distance (max_dist), weights (0-1), decay, and the path to threat factor layers), threat accessibility and sensitivity data (habitat suitability (0-1) and relative sensitivity of land uses to threats) and half-saturation constant.

To simulate the habitat quality for species in tidal flat, the study area was divided into two land use types: Mangrove and Tidal Flat. Tidal Flat was considered as the habitat, while Mangrove was categorized as non-habitat, resulting in habitat suitability parameters of 0 and 1, respectively. Mangrove was designated as the sole threat, with a weight of 1. The impact of the threat factor decreased exponentially with distance from the habitat. The sensitivity of Tidal Flat to the threat factor (Mangrove) was set at 0.5 (chosen as a midpoint due to a lack of relevant research data). Mangrove, being non-habitat, had a sensitivity of 0 to the threat factor, as indicated in Tables 1 and 2.

Table 1. Habitat suitability and sensitivity to each LULC

LULC	Code	Habitat suitability	Sensitivity of mangrove
Mangrove	1	0	0
Tidal Flat	2	1	0.5

Table 2. The maximum distance over which each threat affects habitat quality and weight

Threat	Max_Dist (km)	Weight	Decay
Mangrove	0.5	1	exponential

2.4.2 Coastal Blue Carbon model: The InVEST Coastal Blue Carbon(CBC) model attempts to predict the amount of carbon storage and sequestration in coastal zones at specific time points due to land cover changes. It utilizes a bookkeeping-type approach to model carbon cycling. This method simplifies carbon cycling by accounting for carbon stored in three main carbon pools: biomass, sediment carbon (i.e., soil), and long-term standing dead carbon (i.e., litter) (Natural Capital Project, 2023). The primary equation used for calculating coastal blue carbon is as follows:

$$S_{p,t} = \begin{Bmatrix} S_{p,t-1} + N_{p,t} \; if \; t > t_{baseline} \\ S_{p,t_{baseline}} \quad if \; t = t_{baseline} \end{Bmatrix} \qquad (3)$$

$$N_{p,t} = \begin{Bmatrix} -1 \cdot E_{p,t} \; if \; carbon \; is \; emitting \\ A_{p,t} \; if \; carbon \; is \; accumulating \end{Bmatrix} \qquad (4)$$

$$E_{p,t} = D_{p.s} \cdot \left(0.5^{\frac{t-(s+1)}{H_{p,s}}} - 0.5^{\frac{t-s}{H_{p,s}}} \right) \qquad (5)$$

$$D_{p,s} = S_{p,s} \cdot M_{p,s} \qquad (6)$$

where $t_{baseline}$ = the year of the baseline land cover
p= carbon pool
$S_{p,t}$ = Carbon stocks
$N_{p,t}$ = Net sequestration
$E_{p,t}$= emissions
$D_{p,s}$= The volume of disturbed carbon

In the research, the Coastal Blue Carbon model was used to quantify the carbon sequestration or emission (Mg C ha^{-1}) by mangroves until the year 2023 due to Land Use and Land Cover Change (LULCC) impacts. The required input data include: Biophysical Table (Table 3.), transition matrix (obtained from the CBC Preprocessor; "accum" is input in the cell for Carbon Accumulation, "NCC" for No Carbon Change, and "disturb" for Carbon Disturbance, which users can further modify as "low-impact-disturb," "med-impact-disturb," or "high-impact-disturb" when carbon disturbance occurs), LULC maps and LULC lookup table (indicating whether each land use type qualifies as coastal blue carbon habitat.). The Biophysical Table includes information about carbon stocks and carbon accumulation rates for various carbon pools, biomass, and soil disturbance impacts, as well as carbon half-life. The carbon stocks and accumulation rate data were referenced from Huang (2016), specific to the Fangyuan Wetland. Biomass and soil disturbance impact rates represent the percentage of carbon loss resulting from LULCC, using values from the global carbon storage and accumulation rate database provided by the InVEST CBC model (Natural Capital Project, 2023).

Table 3. Biophysical Table

LULC code	1	2
LULC class	Mangrove	Tidal Flat
biomass-initial, units: Mg C ha^{-1}	87.24	0
soil-initial, units: Mg C ha^{-1}	157.61	0
litter-initial, units: Mg C ha^{-1}	0	0
biomass-half-life, units: year	15	0
biomass-low-impact-disturb	0.5	0
biomass-med-impact-disturb	0.5	0
biomass-high-impact-disturb	1	0
biomass-yearly-accumulation, units: Mg C $\text{ha}^{-1}\ \text{yr}^{-1}$	17.91	0
soil-half-life, units: year	7.5	0
soil-low-impact-disturb	0.3	0
soil-med-impact-disturb	0.5	0
soil-high-impact-disturb	0.66	0
soil-yearly-accumulation, units: Mg C $\text{ha}^{-1}\ \text{yr}^{-1}$	2.81	0
litter-yearly-accumulation, units: Mg C $\text{ha}^{-1}\ \text{yr}^{-1}$	0	0

2.5 Scenario analysis

We conducted simulations in Fangyuan to assess the impact of different mangrove management scenarios on ecosystem services. Using Python in Google Colab, we generated land-use maps for three positions (top, middle, and bottom) with sequential ten percent reductions in mangrove area (from 10% to 90%). We installed the "rasterio" package and imported essential packages like numpy, matplotlib.pyplot, rasterio, and Image for tasks such as data processing and visualization. By employing for-loops, we selected regions and created post-harvest land-use and mangrove distribution maps in TIFF format for further analysis.

3. RESULTS

3.1 The impact of changes in mangrove area over the years on ecosystem services

3.1.1 Mangrove Spatial Distribution: The study area encompasses approximately 134 hectares. Figures 3a to 3d illustrate the distribution of Fangyuan mangroves for the years 1996, 2006, 2017, and 2023. The areas without mangroves are defined as tidal flats, with their respective sizes detailed in Table 4. The mangrove area underwent nearly a fourfold increase from 1996 to 2006. Although the growth rate slowed by 2017 compared to 2006, it still approached approximately 30 hectares. Presently, due to ongoing research projects, thinning initiatives, and government planning and management, the area has slightly reduced to around 27 hectares.

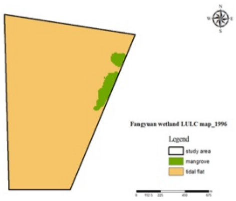

Figure 3a. LULC_1996

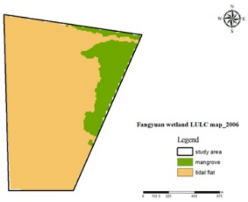

Figure 3b. LULC_2006

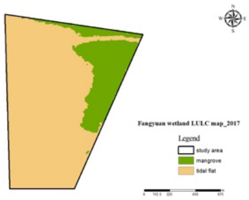

Figure 3c. LULC_2017

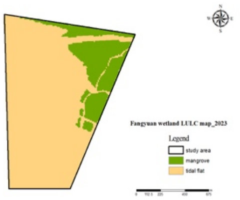

Figure 3d. LULC_2023

Table 4. The area of mangroves and tidal flats in the study area of Fangyuan Wetland.

year	The area of mangroves (ha)	The area of tidal flats (ha)
1996	4.57	129.43
2006	20.92	113.08
2017	29.11	104.89
2023	26.99	107.01

3.1.2 Ecosystem Service Assessment - Habitat Quality: Figures 4a to 4d show habitat quality levels in the study area for 1996, 2006, 2017, and 2023 (Table 5). Habitat quality is lowest in mangrove areas and improves with distance from them. As mangrove area increased, habitat quality decreased by about 58.79% from 1996 to 2006 and 38.35% from 2006 to 2017. However, from 2017 to 2023, with a slight mangrove area reduction, habitat quality increased by approximately 14.80%.

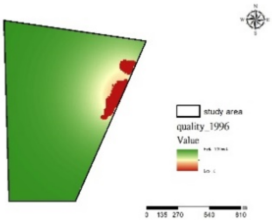

Figure 4a. habitat quality_1996

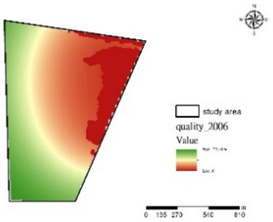

Figure 4b. habitat quality_2006

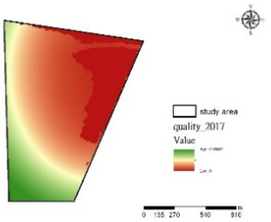

Figure 4c. habitat quality_2017

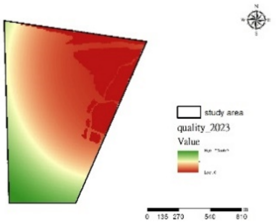

Figure 4d. habitat quality_2023

3.1.3 Ecosystem service assessment – Carbon stock: Here are the maps displaying carbon stock distribution for each year (Figure 5a to 5d), and the corresponding values can be found in Table 6. From 1996 to 2006, total carbon stock increased by about 84.59%. However, when averaged over the mangrove area, carbon stock per unit area decreased by roughly 59.59%. Moving on to 2006 to 2017, there was a significant total carbon stock increase of approximately 230.39%, with the average carbon stock per unit area showing an increase of about 137.67%. Finally, from 2017 to 2023, due to a slight mangrove area reduction and a shorter accumulation period of six years, the increase in carbon stock was relatively smaller, at approximately 58.14%, with the average carbon stock per unit area increasing by about 70.58%.

Figure 5a. carbon stock_1996

Figure 5b. carbon stock_2006

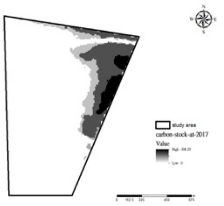

Figure 5c. carbon stock_2017

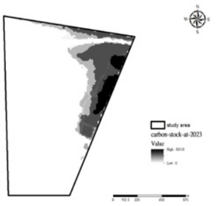

Figure 5d. carbon stock_2023

Table 5. The habitat quality of the the study area.

year	MEAN
1996	0.9039
2006	0.3723
2017	0.2296
2023	0.2636

Table 6. The carbon stock of the study area.

year	Sum (Mg C)	Mean (Mg C ha^{-1})
1996	1118.96	244.84
2006	2065.58	98.73
2017	6833.95	234.76
2023	10806.87	400.40

3.1.4 Ecosystem Service Assessment - Carbon Sequestration: Figure 6 shows the total carbon sequestration over the analysis years, which is the net carbon accumulation after accounting for emissions. The carbon sequestration values for each period are provided in Table 7. Between 2006 and 2017, carbon sequestration increased by approximately 403.48% compared to the previous decade (1996 to 2006), with an average annual increase of about 357.63%. From 2017 to 2023, there was a decrease of approximately 16.68% compared to the period from 2006 to 2017, with an average annual increase of about 30.92%. In the 27-year period in Fangyuan Wetland, the total carbon sequestration was 9687.90 Mg C, averaging 345.99 Mg C yr^{-1}.

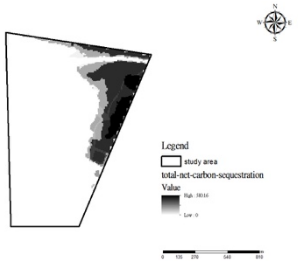

Figure 6. total net carbon sequestration

Table 7. The total net carbon sequestration of the Fangyuan Wetland in the study area.

Time Periods	Total (Mg C)	per year (Mg C yr^{-1})
1996-2006	946.90	94.69
2006-2017	4768.08	433.46
2017-2023	3972.92	567.56
1996-2023	9687.90	345.99

3.2 The Impact of Simulated Thinning Scenarios on Ecosystem Services

3.2.1 Scenario Analysis Settings: To evaluate the impact of different mangrove thinning scenarios on the overall provision and spatial distribution of ecosystem services, the following parameters were applied. Thinning was simulated in three directions (top, middle, and bottom), with each subsequent scenario involving an additional 10% reduction in mangrove area. The resulting land use maps for the study area, generated through Python simulations, are displayed in Figures 7a-7c (depicting a 10% reduction in mangrove area as an example).

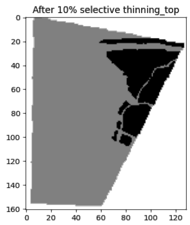

Figure 7a. After 10% thinning_top.

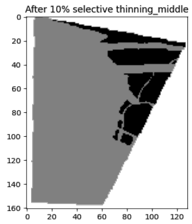

Figure 7b. After 10% thinning_mid.

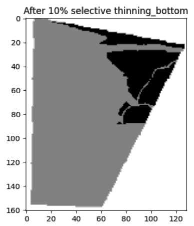

Figure 7c. After 10% thinning_bot.

3.2.2 Ecosystem Service Assessment - Habitat Quality: In line with the scenario settings, Figures 8a-8c illustrate the habitat quality of the study area following simulated mangrove thinning, with a specific example showing a 50% reduction in mangrove area. The calculated habitat quality values for each thinning scenario are presented in Figures 9a-9c, allowing for a comparison with the habitat quality in 2023. As the mangrove area decreases, there is a gradual improvement in the average habitat quality within the study area. While there are numerical variations based on the location of thinning, these differences are not considered significant.

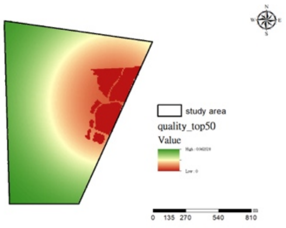

Figure 8a. Habitat quality-thinning50_top

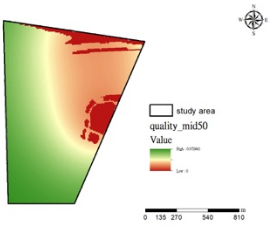

Figure 8b. Habitat quality-thinning50_mid

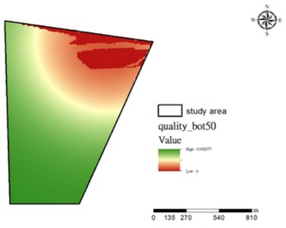

Figure 8c. Habitat quality-thinning50_bot

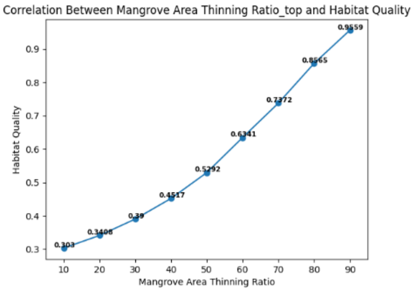

Figure 9a. Values of habitat quality_top.

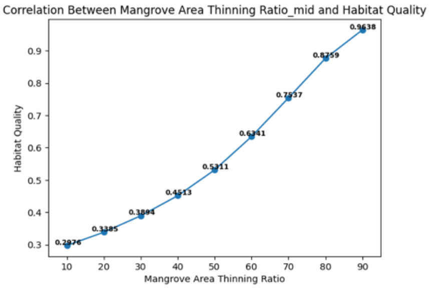

Figure 9b. Values of habitat quality_mid.

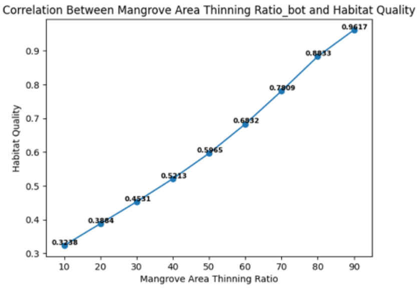

Figure 9c. Values of habitat quality_bot.

3.2.3 Ecosystem Service Assessment - Carbon Stock: In accordance with the scenario settings, the simulated carbon stock in the study area following mangrove thinning is illustrated in Figures 10a-10c, with examples featuring three different locations and a 50% reduction in mangrove area. Figures 11a-11c present the computed carbon stock values for each thinning scenario, and these outcomes are juxtaposed with the carbon stock in 2023. As the mangrove area diminishes, so does the carbon stock within the study area. Similar to the habitat quality assessment, distinct thinning scenarios across various locations yield variable values, albeit without any statistically significant differences.

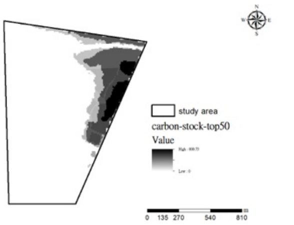

Figure 10a. Carbon stock-thinning50_top

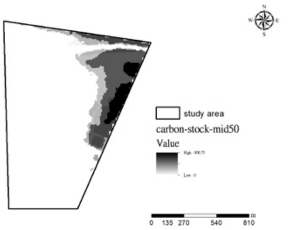

Figure 10b. Carbon stock-thinning50_mid

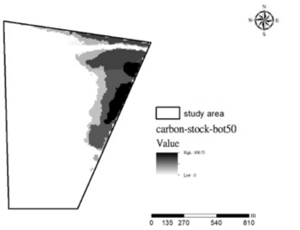

Figure 10c. Carbon stock-thinning50_bot

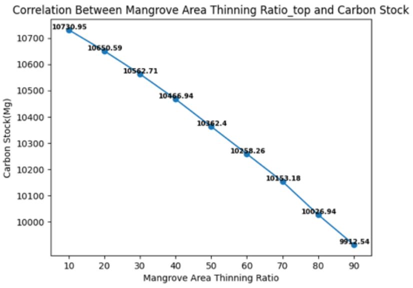

Figure 11a. Values of Carbon stock_top.

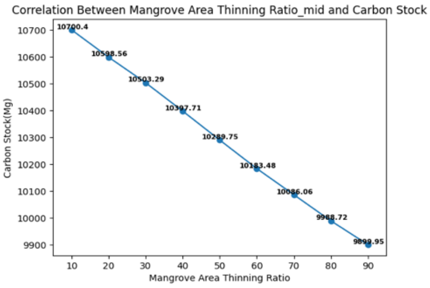

Figure 11b. Values of Carbon stock_mid.

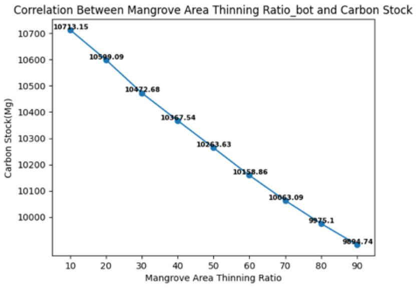

Figure 11c. Values of Carbon stock_bot.

4. DISCUSSION

The research findings indicate that from 2006 to 2017, there was a significant slowdown in the annual decline in habitat quality and degradation rate compared to the preceding period. This deceleration is believed to be a result of the reduced growth rate of the mangrove area during this period. In 2023, there was a decrease of 2.12 hectares in the mangrove area compared to 2017, resulting in a positive change in habitat quality. The annual cumulative value of coastal blue carbon also exhibited a more gradual increase during this period. In 1996, the average carbon stock per hectare was higher, likely because the initial carbon stock dominated the first-year values. However, by 2006, despite continuous cumulative carbon calculations, the area had grown approximately fourfold, resulting in relatively lower average values. In subsequent years, as the rate of area growth slowed compared to the initial period, the average value of carbon accumulated over time increased gradually. The Coastal Blue Carbon model considers carbon accumulation rates for various carbon pools and assumes linear stock and accumulation of carbon over time between transitions (Natural Capital Project, 2023). Even if the mangrove area in the study area did not increase and even decreased from 2017 to 2023, the total carbon stock in 2023 was still greater than in 2017. This aligns more closely with the actual situation in the study area compared to the Carbon Storage and Sequestration model.

From the designed thinning scenarios, it can be observed that the quantity of mangrove area has a more significant impact on ecosystem services, while the factor of thinning location is less pronounced. Habitat quality exhibits a negative correlation with mangrove area, while carbon storage demonstrates a positive correlation. The model also assumes that carbon affected by disturbance events will exponentially decay over time. The results indicate that even with a 90% reduction in mangrove area, there is still nearly 9900 Mg C of carbon stock, approximately 91% of the pre-thinning levels.

This demonstrates that a substantial amount of carbon is stored in soil sediments, consistent with the findings of Donato et al. (2011), who suggested that soil carbon can constitute 49-98% of the total carbon storage and continues to be released over time. Additionally, the study by Sweetman et al. (2010) indicated that the short-term carbon cycling dynamics in mangrove sediments may fundamentally differ from non-invaded tidal flat sediments for at least 6 years after the removal of overlying mangrove vegetation.

During InVEST model execution, resource limitations and lack of local data led to parameter substitutions from previous studies. The model itself has simplifications and limitations that may introduce some error into the results.

5. CONCLUSIONS

Prior studies have shown that mangrove forests in Fangyuan wetlands lead to sediment accumulation and landward expansion, impacting wetland area and species habitats. However, large-scale clearing is impractical. Mangroves are important blue carbon sinks, presenting a challenge for managers to balance through controlled thinning and planning. Few studies in Taiwan have simultaneously assessed habitat quality and coastal blue carbon under various thinning scenarios using simulation. This study uses satellite imagery and the InVEST model to evaluate ecosystem service changes in the Fangyuan wetlands and the impact of red mangrove thinning. Understanding the trade-off between habitat quality and coastal blue carbon quantity and distribution will guide future management decisions.

References and Bibliography

Bera, B., Bhattacharjee, S., Sengupta, N., Shit, P. K., Adhikary, P. P., Sengupta, D., & Saha, S. (2022). Significant reduction of carbon stocks and changes of ecosystem service valuation of Indian Sundarban. Scientific Reports, 12(1), 1-17.

Changhua County Government (2014). "Changhua Coastal Sustainable Master Plan - Mangrove Ecosystem Resource Survey and Analysis Research Project - Final Report." Research Project Subsidized by the Construction and Planning Agency (Water Resources Agency, Ministry of Economic Affairs).

Changhua County Government (2020). "2019 Changhua County National Water Environment Improvement Plan - Fangyuan Wetland Mangrove and Surrounding Comprehensive Environmental Improvement Plan - Ecological Checklist (Construction Phase) - 2nd Survey Report for 2019."Barbier, E. B., Hacker, S. D., Kennedy, C., Koch, E. W., Stier, A. C., & Silliman, B. R. (2011). The value of estuarine and coastal ecosystem services. Ecological monographs, 81(2), 169-193.

Chan, Wei-Hsun, Cheng, Ko-Feng, Lin, Chun-Cheng, & Chiu, Chi-Jung (2020). "Assessing the Impact of Land Use Change on Ecosystem Services Using InVEST: A Case Study of Lianhua Lake Area." Quarterly Journal of Chinese Forestry, 53(1), 1-17.

Chen, Tzu-Ling, Lai, Hong-Ko, & Chiu, Ying-Hao (2021). "Assessing the Impact of Pond Changes on Ecosystem Services in Taoyuan Area Using Satellite Imagery Interpretation." Geographical Research, (100), 71-100.

Donato, D. C., Kauffman, J. B., Murdiyarso, D., Kurnianto, S., Stidham, M., & Kanninen, M. (2011). Mangroves among the most carbon-rich forests in the tropics. Nature geoscience, 4(5), 293-297.

Hoyer, R., & Chang, H. (2014). Assessment of freshwater ecosystem services in the Tualatin and Yamhill basins under climate change and urbanization. Applied Geography, 53, 402-416.

Huang, Jih-Sheng (2016). "The Impact of Mangrove Thinning on Carbon Sequestration." (Master's thesis, National Chung Hsing University)

Lin, Hsin-Chu, Chen, Chi-Ling, Chen, Tian-Shui, Lee, Shih-Bo, Sung, Ming-Ju, Lin, Wei-Jen, Chen, Wei-Chung, Chen, Chia-Yi, Chen, Yan-Kuang, & Chang, En-Tse (2018). 106-107 Wetland Carbon Sequestration Survey Project. Subsidized Research Project, Department of Urban and Rural Development, Construction and Planning Agency, Ministry of the Interior.

Lin, Hui-Hsuan, Chien, Yu-Lang, & Lin, Hsin-Chu (2019). "Carbon Storage Benefits of Western Taiwan Coastal Wetlands." Agricultural Economics Journal, 25(1), 1-26.

Lee, Shih-Bo (2015). "Carbon Budget Model for Tainan Qi Gu Mangrove." (Master's thesis, National Chung Hsing University)

Mcleod, E., Chmura, G. L., Bouillon, S., Salm, R., Björk, M., Duarte, C. M., ... & Silliman, B. R. (2011). A blueprint for blue carbon: toward an improved understanding of the role of vegetated coastal habitats in sequestering CO2. Frontiers in Ecology and the Environment, 9(10), 552-560.

Natural Capital Project, 2023. InVEST 3.13.0. Stanford University, University of Minnesota, Chinese Academy of Sciences, The Nature Conservancy, World Wildlife Fund, Stockholm Resilience Centre and the Royal Swedish Academy of Sciences. https://naturalcapitalproject.stanford.edu/software/invest

Rimal, B., Sharma, R., Kunwar, R., Keshtkar, H., Stork, N. E., Rijal, S., ... & Baral, H. (2019). Effects of land use and land cover change on ecosystem services in the Koshi River Basin, Eastern Nepal. Ecosystem services, 38, 100963.

Robertson, A. I., & Alongi, D. M. (1992). Tropical mangrove ecosystems (Vol. 41). American Geophysical Union.

Sweetman, A. K., Middelburg, J. J., Berle, A. M., Bernardino, A. F., Schander, C., Demopoulos, A. W. J., & Smith, C. R. (2010). Impacts of exotic mangrove forests and mangrove deforestation on carbon remineralization and ecosystem functioning in marine sediments. Biogeosciences, 7(7), 2129-2145.

Tomlinson, P. B. (1986). The botany of mangroves. Cambridge University Press.

Twilley, R. R., Chen, R. H., & Hargis, T. (1992). Carbon sinks in mangroves and their implications to carbon budget of tropical coastal ecosystems. Water, Air, and Soil Pollution, 64, 265-288.